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Omnidirectional vibration sensor based on fiber Bragg gratings in a seven-core fiber

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ABSTRACT

We report an orientation-sensitive omnidirectional vibration sensor based on fiber Bragg gratings (FBGs) inscribed in a seven-core optical fiber. By monitoring the central wavelength shifts of three FBGs in the central core and two outer cores, orientation information in 0-180° range as well as the acceleration value are obtained. The performance of the vibration sensor is characterized at different frequencies, orientations and accelerations. Comparison results for orientation discrimination using different groups of outer cores are investigated to enhance the reliability of the vibration sensor. The experimental results demonstrate an accuracy as high as 0.01° for orientation discrimination. The compact size and simple structure make the vibration sensor potentially superior in industrial applications where precise monitoring of the orientation is a necessity.

Keywords: Fiber Bragg grating, multi-core fiber, vibration sensor, orientation discrimination

1. INTRODUCTION

During the past two decades, fiber-optic vibration sensors have attracted universal research interests for their distinct properties, including inherent electrical isolation, immunity to electromagnetic interference and signal multiplexing capabilities [1, 2]. Orientation information is one of the most critical parameters in a vibration measurement system, especially when the vibration source is unknown, such as a cantilevered microwire [3]. Generally, multiple single-axis vibration sensors are used to determine the vibration directions, making the system complex. Likewise, detection of the vibration orientation is dependent on the placement of individual sensors, which limits the detection range as well. As a result, mechanical measurements in a vibration system capable of omnidirectional orientation discrimination remain challenging [4].

In order to address this problem, various kinds of fiber-optic omnidirectional vibration sensors have been proposed. The sensor is supposed to be capable of detecting the orientation in 0-180° as well as the acceleration value during the vibration process. For example, Rong et al. introduced an orientation-sensitive vibration sensor based on tilted fiber Bragg gratings (TFBGs) inscribed in the cladding of a thin-core fiber [5]. Through detection of the cladding mode reflection, the vibration measurements were demonstrated to be strongly dependent on the orientation. However, this sensor was able to provide only the results of orientation dependence rather than direct identification. Moreover, Bao et al. demonstrated another vibration sensor based on output power detection of orthogonal FBGs in a multi-clad fiber [4]. However, this particular sensor was incapable of distinguishing specific orientations under random circumstances.

In this work, we present an FBG-based omnidirectional vibration sensor in a multi-core fiber (MCF). Sensitivity of the sensor is investigated under different orientations ranging from 0 to 180° in steps of 10°. The results demonstrate that vibration frequency, orientation together with the acceleration value can be obtained simultaneously in a single measurement with the use of a central core and two outer cores which are not in a straight line. The orientation accuracy when distinguishing orientations is measured with two combinations of the outer cores. Accuracy range of 0.01 to 2.789° and 0.01 to 2.963° are achieved for the two combinations of the outer cores, where a relatively low accuracy is probably caused by a high acceleration value. Moreover, the central core of the fiber can be used for temperature compensation, which makes the sensor to be temperature insensitive.

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2. THEORY

The basic principle of the vibration sensor is based on monitoring the Bragg wavelength shifts of the FBGs inscribed in the seven-core MCF during vibrations. Figure 1(a) shows the cross-section of the MCF used in the sensor, with a central core (i.e. core 1) and six outer cores (i.e. core 2-7) arranged in a hexagonal structure. The MCF, purchased from YOFC, has core and cladding diameters of ~8 and ~150 µm, respectively. Pitch d_i between the outer core and the central core 1 is ~42 µm, as shown in Fig. 1(a). In order to enhance the photosensitivity, the fiber was loaded in a hydrogen chamber at a pressure of 100 bar and a temperature of ~80 °C for 3 days prior to FBG inscription. Using the beam scanning technique, a 213 nm solid-state laser (Xiton Photonics, Impress 213) and a uniform phase mask with 1069 nm period (Ibsen Photonics) were used to inscribe FBGs in all the seven cores simultaneously. The scanning speed was 0.01 mm/s and the grating length was 10 mm. After the FBG inscription, a 7-to-1 fan-out device was connected to the MCF using a fiber fusion splicer (Fujikura, LZM-100). The reflection spectra of the FBGs were analyzed by an interrogator (Micron Optics, sm130) with an acquisition rate of 2000 Hz.

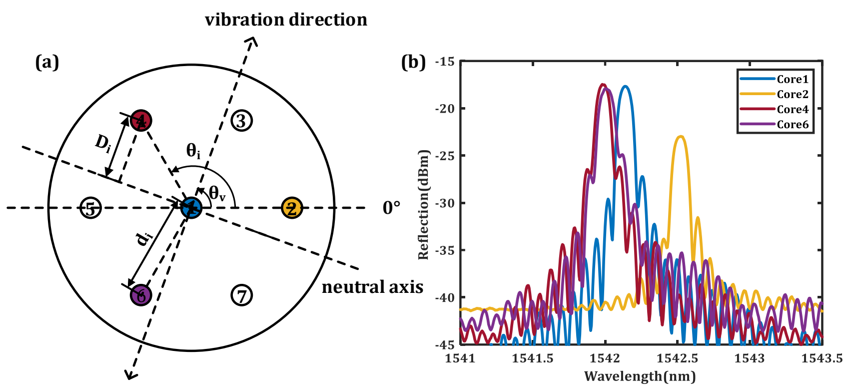

Figure 1. (a) Cross-section of the fiber cores with the defined geometrical parameters. (b) Reflection spectra of the FBGs inscribed in core 1, 2, 4 and 6.

In order to distinguish the vibration orientation, two randomly chosen outer cores which are not in a straight line with the central core were used to reconstruct the orientation. Here, we have used core 1, 2, 4 and 6 and the spectra of the FBGs in these cores are plotted in Fig. 1(b). There is a slight difference in the Bragg wavelengths, where λ_i (i = 1, 2, 4, 6) for each core is 1542.14, 1542.52, 1541.98 and 1542 nm, respectively. This may be due to the non-uniform UV exposure caused by the different spatial distribution of the cores [6]. The vibration-induced strain ε_i on the i^{th} FBG can be described as

$$\varepsilon_i = \frac{d_i}{R}\sin(\theta_v + \theta_i), \tag{1}$$

where d_i is the pitch illustrated in Fig 1(a). θ_v and θ_i indicate the vibration orientation and angular position for each outer core i, respectively. R is the vibration-induced bending radius. When a random vibration occurs, outer cores respond differently according to their relative position to the neutral plane, while central core is insensitive to the vibration. With the use of Bragg wavelength shifts $\Delta\lambda_i$ in two outer cores which are not aligned in a straight line with the central core, the reconstructed vibration orientation can be described as

$$\theta_v = \arctan\left(\frac{\dfrac{\Delta\lambda_i}{\lambda_i}\sin\theta_j - \dfrac{\Delta\lambda_j}{\lambda_j}\sin\theta_i}{\dfrac{\Delta\lambda_j}{\lambda_j}\cos\theta_i - \dfrac{\Delta\lambda_i}{\lambda_i}\cos\theta_j}\right), \tag{2}$$

where i and j are the chosen outer core numbers. In the experiment, core 2, 4 and 6 are chosen, as shown in Fig. 1. The corresponding angular positions are 0, 2π/3 and -2π/3, respectively.

3. OMNIDIRECTIONAL VIBRATION EXPERIMENT

Figure 2 depicts the experimental setup of the omnidirectional vibration sensor. The seven-core MCF with FBGs was used as the sensing probe, which was fixed on a fiber rotator (Thorlabs, HFR007) with a tunable orientation from 0 to 180° in steps of 10°. Here, we define the orientation of 0° when core 2, 1 and 5 are aligned horizontally, as illustrated in Fig. 1(a). The vibration sensor was then mounted on the top of a shaker (Bruel & Kjaer, Type 4808) which was driven by a sinusoidal signal generator. In order to characterize the performance of the vibration sensor, it was measured under different frequencies, orientations and accelerations. A series of sine vibration waves with vibration frequencies ranging from 8 to 35 Hz was applied to the accelerometer with a free-fiber length L of 66 mm, while the grating was kept 2 mm away from the fixed point on the rotator. During the measurement, the acceleration was increased from 0.2 to 10 g, where g = 9.8 m/s^2. A high-resolution interrogator was connected to the output of the fan-out device to monitor the Bragg wavelength shifts of FBGs in core 1, 2, 4 and 6.

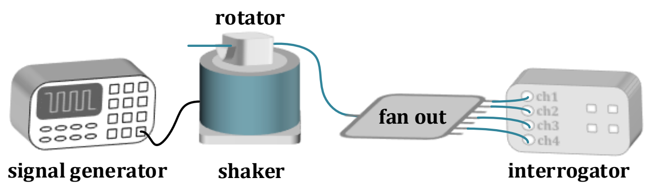

Figure 2. Schematic setup of the omnidirectional vibration sensor.

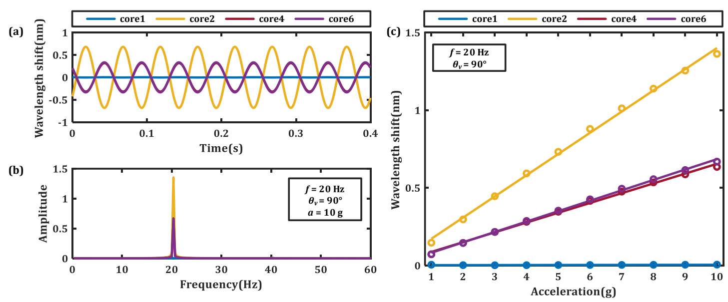

Figure 3. (a) Real-time wavelength shifts of FBGs in core 1, 2, 4 and 6 and (b) corresponding FFT spectrum when f = 20 Hz, θ_v = 90° and a = 10 g; (c) linear response of wavelength shifts versus the applied acceleration values for the FBGs in core 1, 2, 4 and 6 at f = 20 Hz and θ_v = 90°.

Curves in Fig. 3(a) display the wavelength shifts of the FBGs in core 1, 2 ,4 and 6 in time domain, at a vibration frequency of f = 20 Hz, vibration orientation of θ_v = 90° and an acceleration value of a = 10 g. It can be clearly observed that the FBGs in core 2 and 4 experience an opposite wavelength shift, while it remains the same between core 4 and 6, since they are located at the same side of the neutral plane which is different from core 2, under a vibration orientation of 90°. In addition, amplitude of the wavelength shift is dependent on the strain ε_i applied to each FBG during vibration, which is proportional to the distance D_i (i.e. i = 2, 4 and 6) from the core of interest to the neutral plane, as shown in Fig. 1(a). When the vibration orientation is set to be 90°, D_4 and D_6 have the same value due to their angular positions. As a result, they share a similar curve in the time domain waveforms. In contrast to the responses of the outer cores, the FBG inscribed in core 1 shows insensitivity to vibration because it lies on the neutral plane at all times. By conducting fast Fourier transfer (FFT) of the time domain waveforms in Fig. 3(a), the vibration frequency is easily obtained, and the spectra are shown in Fig. 3(b). The measured frequency matches well with the input frequency from the signal generator. Furthermore, the maximum wavelength shifts as a function of the applied accelerations from 1 to 10 g are plotted under the scenario where f = 20 Hz and θ_v = 90° in Fig. 3(c). Slopes of the linear responses represent the measurement sensitivities under these conditions for the four cores, which are 0.27, 136.48, 63.58 and 67.55 pm/g for core 1, 2, 4 and 6, respectively. It is noted that, there is slight difference between the sensitivity for core 4 and 6, which may result from the installation error when mounting the fiber on the shaker, possibly due to a minute tilt of core 2, 1 and 5 which are supposed to be horizontal.

In order to investigate the capability of the orientation discrimination characteristics of the sensor, different accelerations were applied, together with various orientations. During the vibration process, D_i changes with the vibration orientation, which periodically changes the applied strain on the fiber cores. Consequently, vibration sensitivity varies with the change of orientation. Figure 4(a) shows the dependence of vibration sensitivity on the orientation for core 2, 4 and 6 over a range of 0-180° in steps of 10° under a frequency of 20 Hz. As expected, at a certain orientation, vibration sensitivities respond differently for core 2, 4 and 6. There is a 60° phase shift in the sensitivity curves for these three cores, just like the geometrical angle between them and the central core. Besides, the orientation accuracy which is defined as the difference between the measured and ideal ones, is accounted in analyzing the performance of the orientation reconstruction. As shown in Fig. 4(b), the accuracy ranges from 0.01 to 2.789° for core 2 and core 4 (group 1), and 0.01 to 2.963° for core 2 and core 6 (group 2). Moreover, various accelerations from 1 to 10 g were applied to the sensor under each orientation. Figure 4(c) shows the measured orientations under different accelerations when the actual vibration orientation is set to be 20°. It is noted that both groups of the outer cores can distinguish the orientation well, while lacking any obvious difference in the reconstructed orientations under a specific acceleration.

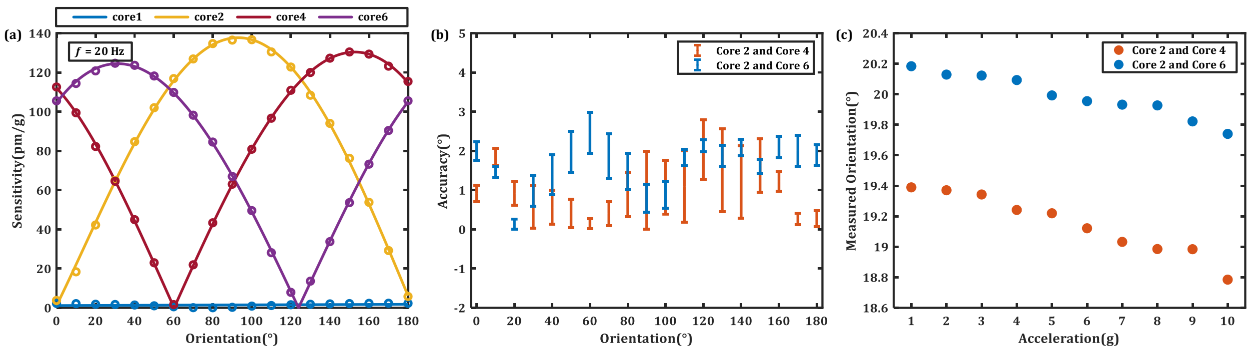

Figure 4. (a) Orientation dependent vibration sensitivities of FBGs in core 1, 2, 4 and 6 under f = 20 Hz. (b) Orientation accuracy under different combinations of outer cores. (c) Measured orientations applied with different accelerations when θ_v = 20° under different combinations of outer cores.

4. CONCLUSION

In conclusion, we have proposed an FBG-based omnidirectional vibration sensor capable of obtaining information of the vibration orientation, as well as the acceleration simultaneously. With the use of three of the seven cores in the MCF, the sensor demonstrates capability to distinguish the orientation under random vibrations. Different outer cores are chosen for the orientation reconstruction, with accuracies ranging from 0.01 to 2.789° and 0.01 to 2.963° under different combinations. The similar accuracy makes the sensor more reliable in differentiating the orientation.

5. ACKNOWLEDGEMENT

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